# Resilient Modulus, Tensile Strength, and Simple Shear Test to Evaluate Moisture Sensitivity and the Performance of Lime in Hot Mix Asphalt Mixtures


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## ABSTRACT

The use of hydrated lime in hot mix asphalt (HMA) is an accepted practice used by many state highway departments. However, there are various techniques of introducing lime into the mixture and several factors that favor one method over another. The goal of this study was to evaluate the mechanical properties of lime-treated HMA mixtures before and after multiple cycles of freeze-thaw moisture conditioning. The mechanical tests used were the resilient modulus, tensile strength, and simple shear test. In addition, the study compared the three test procedures for evaluating the moisture sensitivity of HMA mixtures.

With the addition of lime and after multiple cycles of freeze-thaw moisture conditioning, all mixtures demonstrated an enhanced ability to retain the original measured properties. The four methods of lime treatment: dry lime to moist aggregates, lime slurry to dry aggregates, and each application method receiving either a 48 hour marination time or no marination time, were found to be statistically equivalent.

The evaluation of moisture sensitivity of a HMA mixture is possible with all three mechanical test procedures. Resilient modulus proved to be the best technique for measuring small reductions in strength. When the loss of strength due to moisture sensitivity exceeded 20 percent, the measurement of tensile strength provided a better statistical correlation.

## INTRODUCTION

Moisture induced damage of hot mix asphalt (HMA) pavement can drastically reduce a pavement's expected design life. The phenomenon is referred to as stripping and results when moisture causes a loss of bond between the aggregate and asphalt binder. Once the HMA mixture is damaged, a significant reduction in the HMA's internal strength occurs. The moisture damage within the asphalt pavement's structure can manifest into various types of pavement distresses such as fatigue cracking, rutting, and raveling (*1*).

For some pavements, the rate at which the pavement deteriorates due to moisture damage can be reduced by the use of lime as an aggregate additive (2). Studies have shown that lime reduces the potential for moisture to disrupt the adhesive bond that exists between the asphalt binder and aggregate. Some individuals attribute the increase in adhesive strength to changes in the surface chemistry or molecular polarity of the aggregate surface. The result is a stronger bond at the interface between the aggregate and asphalt binder (3).

This paper provides a conclusive investigation of three different test methods to evaluate moisture sensitivity of HMA mixes. In addition, a statistical analysis is used to determine the best method of introducing lime into a HMA mix as an aggregate additive to mitigate moisture damage.

## BACKGROUND

To date, field data and laboratory evaluations of tensile strength in accordance with AASHTO T-283 still provide the most accurate prediction of moisture sensitivity. Although widely accepted as the standard, this laboratory evaluation has a low correlation to actual performance (4). Test methods need to be developed that couple the laboratory evaluation of moisture sensitivity to the observed field behavior of fatigue cracking, rutting, and raveling.

After adopting the use of lime as an aggregate additive in HMA, the Nevada Department of Transportation (NDOT) has observed a reduction in HMA field distresses. However, a quantifiable mechanism to measure the enhanced bonding between the aggregate and asphalt binder continues to elude researchers (5). In addition, the method of introducing the lime as an aggregate additive to the HMA mix is subject to question. In the field, the application of dry lime to moist aggregates does not always result in uniform coverage on the aggregate's surface. To optimize coverage, NDOT has experimented with a lime slurry application and the use of a mandatory marination time, but these alternatives increase operation costs. Therefore, NDOT needed a quantitative evaluation to justify which method of lime application provides a HMA mixture the best resistance to moisture damage.

## OBJECTIVE

The objective of this research was to use multiple freeze-thaw (F-T) cycles of moisture conditioning and a statistical analysis to evaluate:

1. If the use of lime as an aggregate additive reduces the moisture susceptibility of the HMA mixture;
2. If the method of lime application affects the moisture sensitivity of the HMA mixture;
3. If a relationship exists among the mixture's mechanical properties when evaluated by three different test procedures;
4. Which of the three mechanical test procedures best serves the user in analyzing a mixture's sensitivity to moisture.

## SCOPE

A total of 15 HMA mixtures were evaluated in this study. Mixture variables included aggregate source, grade of asphalt binder, method of lime application, and marination time. Specimens were subjected to multiple cycles of F-T conditioning. Resilient modulus, tensile strength, and permanent shear strain were the measured mechanical properties.

## EXPERIMENTAL DESIGN

Two aggregate sources were used with three grades of asphalt binder to formulate three aggregate asphalt binder combinations. Each of the three aggregate asphalt binder combinations was then subdivided into five mixtures that were defined by the method of lime application and marination time. One of the five mixes was the control and did not utilize lime in the mix design. This mix is referred as "no-lime". The other four mixes were fabricated with lime treated aggregates: dry lime to moist aggregates, lime slurry to dry aggregates, and each application method receiving either a 48 hour marination time or no marination time. A project matrix for the experimental design and number of specimens required is summarized in Table 1 for the 15 HMA mixes represented in this study.

**Materials**

Aggregates referenced as Lockwood were from a quarry located approximately ten miles east of Reno, Nevada, along Interstate 80. Mineral composition of the Lockwood quarry is felsite and basalt. The Lone Mountain aggregates were obtained from an alluvial deposit located approximately six miles to the northwest of Las Vegas, Nevada. The mineral composition of this deposit is quartzite with a heavy coating of calcium carbonate adhering to the larger aggregates. Crushing created the smaller aggregate, which greatly reduced the surface area covered with calcium carbonate. The aggregates from both sources were blended to represent a Nevada Department of Transportation, Type 2C HMA mixture, having a maximum aggregate size of 25 mm (1 inch).

Three grades of asphalt binder were utilized in this experiment: AC-20P, PG 64-34, and AC-30. Both the AC-20P and PG 64-34 were polymer-modified asphalts. The PG 64-34 and AC-30 were obtained from Koch Materials Company, Wichita, Kansas, while the AC-20P was obtained from Telfer Sheldon Oil Company, Pittsburg, California.

**Specimen Preparation**

Two methods of lime treatment were used. Dry lime refers to a technique of adding five percent water to dry aggregates and distributing the moisture by mixing. Hydrated lime at a rate of 1.5 percent is then mixed with the moistened aggregates.

The lime slurry method also resulted in 1.5 percent hydrated lime being added to the aggregates, but the lime was introduced in the form of a lime-water slurry mixed in a ratio of one to three by weight, respectively.

A 48 hour marination time was used to allow for any pozzolanic reaction that might occur between the aggregates and lime. During this time the moist aggregates and lime were sealed in a plastic container. At the end of the marination period, the aggregates were dried in preparation for mixing. The reference to zero hour marination, as noted on Table 1, indicates the moist aggregates and lime were immediately dried, thus not allowing time for any pozzolanic reaction to occur.

**Moisture Conditioning**

Fabrication of specimens and the determination of air voids were conducted in accordance with AASHTO T-283. A total of nine specimens were required to represent each mix and was comprised of three replications for each moisture conditioning scenario; unconditioned, one cycle F-T conditioning, and multiple cycles of F-T conditioning. Specimens created for multiple cycle F-T conditioning and tested for resilient modulus and tensile strength were subjected to 18 F-T cycles. Because some specimens were unable to complete this rigorous conditioning process, only 12 cycles of F-T conditioning were applied to the permanent shear strain specimens.

**Test Conditions and Response Variables**

Fatigue and rutting damage in pavements can be accelerated by the presence of moisture. The moisture-accelerated distress of fatigue can be attributed to a reduction in pavement stiffness, modulus of elasticity, resilient modulus, and tensile strength. To minimize moisture related rutting in the pavement, the stability of the pavement structure must rely on the resistance to permanent shear strain (6). Thus, in the laboratory and after moisture conditioning, an increase in the measured permanent shear strain signifies the potential for moisture damage to have occurred within the mixture. Conversely, after moisture conditioning specimens for resilient modulus and tensile strength testing, a drop in the measured mechanical property signifies moisture damage has occurred.

The resilient modulus was chosen to diagnose the loss of stiffness and modulus of elasticity while a diametral compressive load was used to determine the indirect tensile strength. Evaluation of a mixture’s resilient modulus was in accordance with ASTM D-4123. The testing temperature was 25°C (77°F) with a loading frequency of 0.33 Hertz.

The response variable, resilient modulus, was evaluated against the predictor variable, the number of F-T conditioning cycles, to compare the methods of lime treatment. After the resilient modulus of the specimen was determined, the tensile strength was determined in accordance with AASHTO T-283.

Permanent shear strain was chosen to evaluate the potential of rutting after the mix had been subjected to moisture damage. This was accomplished using the Simple Shear Test (SST) in accordance with AASHTO TP-7, Procedure F, "Repeated Shear at Constant Height." After moisture conditioning and before gluing the specimens to the platens, the specimens were dried at 21°C (70°F). The response variable was permanent shear strain after 5,000 load cycles.

## STATISTICAL ANALYSIS TECHNIQUES

To evaluate the project objectives, statistical comparisons were performed utilizing the analysis of variance (ANOVA) technique. A one-way, mean pairwise comparison with a pooled variance was performed on each of the three aggregate asphalt binder combinations at a 5.0 percent significance level (alpha=5.0%). Each of the three aggregate asphalt binder combinations is a treatment group, and each treatment group had 15 levels that were represented by the five different mixes of the treatment group times the three methods of moisture conditioning.

For this analysis the statistical model was:

$$Y_{ij} = \mu + T_i + e_{ij}$$

Where $Y_{ij}$ = The response for the i*th* treatment, j*th* sample

$\mu$ = The mean

$T_i$ = Treatment effect for the i*th* treatment

$e_{ij}$ = Random error for j*th* sample of i*th* treatment group

Rejecting the null hypothesis ($H_o$) where the means are assumed equal was based on the F test and associated P value. A least significant difference (LSD) was used to compare the effects of lime by level for each respective treatment group (7). Statistical computations for analyzing the data were performed with software from the SAS Institute and SAS ANOVA macros (8).

A control treatment is necessary to create a benchmark to evaluate the effectiveness of the experimental treatments. Within the 15 levels of treatment for each aggregate asphalt binder combination or treatment group, the control treatments were no-lime specimens and specimens which were not subjected to moisture conditioning. These control treatments have been shaded for identification in the project matrix, Table 1. For ease in referencing these levels of treatment throughout this report, the terminology of no-lime and unconditioned will be used to reference the control treatments.

## RESULTS

Tables 2, 3, and 4 are a tabulation of the results and are used to compare the three treatment groups by test procedure: resilient modulus, tensile strength, and permanent shear strain, respectively. The tables also list a value of one-half the LSD for each treatment group for the given test procedure. The one-half LSD value is used to create a range about the mean for comparison of the mixes and is labeled the lower and upper LSD. Therefore, for pairwise comparison between two mixes, if the LSD ranges overlap, the difference between the mean values for the measured mechanical property is concluded to be not significant. A not significant finding formulates acceptance of the null hypothesis, and the values for the two means compared are concluded to be not statistically different. Conversely, if the ranges do not overlap, then the difference between the mean values is concluded to be significant or statistically different.

### Impact of Lime Treatment on a Mixture's Mechanical Properties

The first objective was to evaluate whether the use of lime as an aggregate additive reduces the moisture susceptibility of the HMA mixture. To demonstrate uniformity within each treatment group, the unconditioned no-lime mixes were compared to the four unconditioned lime treated mixes. For example, in Table 2 the resilient modulus for the Lockwood, AC-20P, no-lime mix has a lower and upper LSD range from 229 to 289. This range overlaps the LSD range of all four Lockwood, AC-20P, lime treated mixes. Thus, the resilient modulus mean value of the no-lime mix is not statistically different than the mean values for the four lime treated mixtures. This methodology was repeated for the treatment groups Lockwood, PG 64-34 and Lone Mountain, AC-30. Therefore, a total of 12 resilient modulus comparisons exist when the no-lime mix is compared to the four lime treated mixes for each of the three treatment groups.

A similar comparison of unconditioned no-lime mixes to the four unconditioned lime treated mixes was performed for tensile strength and permanent shear strain. A summary of the statistical findings for the three test procedures is tabulated in Table 5. When evaluated by the three mechanical test procedures, the unconditioned no-lime mixes were determined to be not statistically different than the four unconditioned lime treated mixes. When notable differences were detected as shown in Table 5 for tensile strength, 8 out of 12, and permanent shear strain, 7 out of 12, the no-lime unconditioned mean values for tensile strength and permanent shear strain were larger than the means of the four lime treated mixes. Because of the inverse relationship in these two measured mechanical properties and prior to moisture conditioning, the addition of lime to HMA could enhance the mixture's tensile strength but has a detrimental impact on the mixture’s ability to resist permanent shear strain.

To establish the effectiveness of using lime as an aggregate additive to resist moisture sensitivity, the no-lime mixes were compared to the lime treated mixes after one and multiple cycles of F-T moisture conditioning. The resilient modulus data shown in Table 2 after one cycle of F-T conditioning are used to demonstrate this comparison. The Lone Mountain, AC-30, no-lime mix has a LSD range from 67 to 174. This range is lower and fails to overlap any of the LSD ranges obtained for the four Lone Mountain, AC-30 lime treated mixes. Thus, the no-lime mix after one cycle of conditioning has a substantial loss in resilient modulus and is statistically different than the lime treated mixes.

For a given test procedure and when comparing the three no-lime mixes to the lime treated mixes after one cycle of F-T conditioning, there are a total of 12 comparisons. As shown in Table 5, the majority of no-lime mixes were found to be statistically different than the lime treated mixes, and in all cases the no-lime mixes had lower strength or higher permanent shear strain than the lime treated mixes. Thus, after one cycle of F-T conditioning, the measured mechanical properties of no-lime mixes were inferior to lime treated mixes.

A similar comparison of mechanical properties of no-lime mixes to the mechanical properties of lime treated mixes after multiple cycles of F-T moisture conditioning was initiated. In this evaluation, all of the no-lime mixes were inferior in strength and permanent shear strain and were found to be statistically different when compared to lime treated mixes. A summary of these findings can be found in Table 5.

**Impact of Lime Application Method on a Mixture’s Mechanical Properties**

The second objective was to assess whether the method of lime application affects the moisture sensitivity of the HMA mixture. This comparison only reviewed the mechanical properties of the lime treated mixes after one and multiple cycles of F-T moisture conditioning. To be superior, a lime treated mix would have to be statistically different than the other three lime treated mixes and have the greatest potential to retain the measured mechanical property of strength or permanent shear strain as determined in the unconditioned state.

As an example of the evaluation and using Table 3, values for tensile strength after one cycle of F-T conditioning are compared. The lower LSD value of 86 for Lockwood, PG 64-34, dry lime, zero hour mix is greater than the upper range value of 85 for lime slurry, 48 hour mix. Thus, after one cycle of F-T conditioning, the dry lime, zero hour method of introducing lime into a HMA appears to provide superior tensile strength for this aggregate asphalt binder combination. In comparing the four lime treated mixes of this treatment group and after one cycle of F-T conditioning, there are six statistical pairwise comparisons.

This same methodology was used to evaluate the lime treated mixes after multiple cycles of F-T conditioning. Again using Table 3 and the Lockwood, PG 64-34 treatment group, the LSD ranges for all four lime treated mixes overlap. Thus, after multiple cycles of F-T conditioning, the four methods of lime treatment are found to be not statistically different. Again, six pairwise comparisons were performed in evaluating the Lockwood, PG 64-34, lime treated mixes after multiple cycles of F-T conditioning.

The six comparisons after one and multiple F-T cycles of conditioning for lime treated mixes of a treatment group were combined for a total of 12 comparisons. The method of lime application in conjunction with the measured mechanical property is summarized in Table 5. The 36 comparisons are the sum of the 12 comparisons by treatment group after one and multiple cycles of F-T conditioning times the three treatment groups.

In summary, the method of lime application did not affect the mechanical properties of the HMA mixtures. In cases where the method of lime application was found to be statistically different, the measured differences in strength and permanent shear strain was negligible and was associated with a given aggregate-asphalt binder combination. For example, in Table 5 for resilient modulus, the six lime treated mixes that were deemed statistically different were all from the treatment group Lockwood, AC-20P, but the lime treated mixes of treatment group Lockwood, PG 64-34 were all found to be not statistically different. Thus, there is no conclusive evidence that any one method of lime treatment would better resist the affects of moisture damage.

**Best Test Procedure for Evaluating Moisture Sensitivity**

In using the analysis of variance (ANOVA) for comparing the data that were generated from the three test procedures, the assumptions for ANOVA, normality and equal variance, were met.

Thus, moisture sensitivity of a HMA can be evaluated by any one of the three test procedures: resilient modulus, tensile strength, and permanent shear strain.

A comparison of percent coefficient of variation (CV) is one method to distinguish which test method provides the user with the highest assurance of repeatability. The CV is derived from the standard deviation divided by the mean. Thus, a smaller variation in test data among the specimens tested results in a lower CV, and the lower the CV value, the greater the chance of repeatability in the test method. Table 6 summarizes the CV for each treatment group by mix, conditioning method, and test procedure. The average CV by conditioning method and test procedure is also listed.

From Table 6, a CV of 10.6 for tensile strength determination would appear to be the best test procedure for evaluating moisture sensitivity. To justify this conclusion, a check of the required specimens for an ANOVA analysis was reviewed. For determining the required specimens, the standard deviation or CV is used in conjunction with the difference between the means of the pairwise comparison (7). For computations and staying within the tolerances of conventional HMA test procedures, "Alpha" and the "Power of the Test" were selected at 0.5 and 0.9, respectively (9). The traditional method of evaluating moisture sensitivity is to compare moisture conditioned specimens to unconditioned specimens. In Table 6, the required specimens are shown for both conditioning methods of one and multiple cycles of F-T conditioning. For a complete test, the required unconditioned specimens would have to match those values shown for either one or multiple cycles of F-T conditioning.

For example, only two specimens would be required for tensile strength testing after multiple cycles of F-T conditioning. One specimen would be conditioned while the other would be the control or unconditioned. This conclusion would support the use of tensile strength testing, but to satisfy the recommendations of ANOVA for tensile strength testing after one cycle of F-T conditioning, a total of 32 specimens would be required. This dramatic increase in the number of specimens is a result of the close proximity of tensile strength means. From Table 3, the average of the tensile strength means for all three treatment groups that were unconditioned was 114 psi while the average of the means after one cycle of F-T conditioning was 101 psi. The difference between the averaged means is only 13 percent.

Conversely, for resilient modulus testing, Table 2, the average of the means for unconditioned is 295 ksi, and after one cycle F-T conditioning, the average of the means is 179 ksi. Therefore, the difference between the averaged means is larger at 64 percent. Thus, when computing resilient modulus specimen requirements for one cycle of F-T conditioning from Table 6, three specimens are needed for conditioning plus three control for a total of six specimens.

In conclusion, when evaluating moisture damage that results in small changes to the strength property and to reduce the required number of specimens per experiment, the nondestructive testing of resilient modulus provides the user with a more definitive result. As the number of F-T cycles of conditioning increases, the variance in evaluating the means of the resilient modulus also increases, but the variance among the means of the tensile strength remained relatively constant, see Table 6. Thus the required specimens for tensile strength testing decreased while specimens for resilient modulus testing increased. Statistical justification for the use of six specimens for tensile strength testing required a difference in excess of 20 percent between the means of the tensile strength for the unconditioned and conditioned specimens while the CV of the data remained constant.

Table 6 also demonstrates the required specimens for using permanent shear strain to evaluate moisture sensitivity. For this test procedure, the required number of specimens is high because of the large CV at 21.9, and the small percent differences between the unconditioned and conditioned means. For example in using the averaged means for shear strain from table 4, after one cycle of F-T conditioning, the difference between unconditioned and conditioned means is only 17 percent and drops to only nine percent after multiple cycles of F-T conditioning.

## CONCLUSIONS

On the basis of the analysis of test results obtained in a controlled laboratory setting, the following conclusions are presented:

1. The use of lime as an aggregate additive reduces the moisture susceptibility of the HMA mixture. In all study comparisons, moisture conditioned, lime treated mixes had an enhanced ability to retain the mechanical properties of resilient modulus, tensile strength, and permanent shear strain. Therefore, in addition to the use of lime to enhance the strength properties of a HMA mix while being subjected to moisture, these new findings support the use of lime in reducing moisture related rutting potential as determined by the simple shear tester.

2. For the aggregate asphalt binders tested, the method of lime application does not affect the moisture sensitivity of the mix. There was not conclusive evidence to statistically classify one of the methods, dry lime and lime slurry, each marinated for zero or 48 hours, as a superior technique for the introduction of hydrated lime into a HMA mix.

3. The retention or loss of mechanical properties due to moisture conditioning can be statistically evaluated by measuring a mixture's resilient modulus, tensile strength, and permanent shear strain. This was made possible by using a pooled variance among the 15 levels for each treatment group associated with this study. The percent coefficient of variation among the three test procedures had a low of 10.6 for tensile strength testing and a high of 21.9 for measuring the permanent shear strain. To meet the requirements of ANOVA when evaluating moisture damage of one HMA mixture, the test data showed that the number of required specimens for a pairwise comparison would vary among the test procedures. Specimen requirements increased as the variance within the test data increased and as a result of the close proximity in the measured means of unconditioned and freeze-thaw moisture conditioned specimens.

4. Resilient modulus is the best test procedure to evaluate a mixture's moisture sensitivity when the percent difference in strength between unconditioned and conditioned specimens is small. If the percent difference in strength between the unconditioned and conditioned specimens exceeds 20 percent, the evaluation of tensile strength is the preferred test procedure. Permanent shear strain can be used to evaluate moisture damage in HMA, but the required number of replications for a statistical comparison becomes impractical.

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**LIST OF TABLES**

**TABLE 1 Project Matrix to Evaluate the Performance of Lime in Hot Mix Asphalt Mixtures.**

**TABLE 2 Resilient Modulus Mean Values at 77°F for Three Replications with the Least Significant Difference for a Treatment Group**

**TABLE 3 Tensile Strength Mean Values for Three Replications with the Least Significant Difference for a Treatment Group**

**TABLE 4 Permanent Shear Strain Mean Values at 50°C for Three Replications with the Least Significant Difference for a Treatment Group**

**TABLE 5 Summary of Statistical Findings by Test Procedure for Comparison of Treatment Method**

**TABLE 6 Percent Coefficient of Variation (CV) and Required Specimens among the Mechanical Test Procedures for each Mix and Freeze-thaw Cycles of Moisture Conditioning**

Table 1. Project matrix to evaluate the performance of lime in hot mix asphalt mixtures.

| Mix by Aggregate Source and Asphalt Binder | Method of Lime Treatment | Marination Time in Hours | Moisture Conditioning Freeze-Thaw Cycles | Required Specimens | |
|---|---|---|---|---|---|
| | | | | Resilient Modulus and Tensile Strength | Permanent Shear Strain |
| Lockwood AC-20P | No-Lime (One HMA Mix) | N/A | Unconditioned | 3 | 3 |
| | | | 1 Cycle | 3 | 3 |
| | | | Multiple Cycles | 3 | 3 |
| | Dry Lime to Moist Aggregates (Two HMA Mixes) | 0 | Unconditioned | 3 | 3 |
| | | 48 | | 3 | 3 |
| | | 0 | 1 Cycle | 3 | 3 |
| | | 48 | | 3 | 3 |
| | | 0 | Multiple Cycles | 3 | 3 |
| | | 48 | | 3 | 3 |
| | Lime Slurry to Dry Aggregates (Two HMA Mixes) | 0 | Unconditioned | 3 | 3 |
| | | 48 | | 3 | 3 |
| | | 0 | 1 Cycle | 3 | 3 |
| | | 48 | | 3 | 3 |
| | | 0 | Multiple Cycles | 3 | 3 |
| | | 48 | | 3 | 3 |
| Lockwood PG 64-34 | No-Lime (One HMA Mix) | N/A | Unconditioned | 3 | 3 |
| | | | 1 Cycle | 3 | 3 |
| | | | Multiple Cycles | 3 | 3 |
| | Dry Lime to Moist Aggregates (Two HMA Mixes) | 0 | Unconditioned | 3 | 3 |
| | | 48 | | 3 | 3 |
| | | 0 | 1 Cycle | 3 | 3 |
| | | 48 | | 3 | 3 |
| | | 0 | Multiple Cycles | 3 | 3 |
| | | 48 | | 3 | 3 |
| | Lime Slurry to Dry Aggregates (Two HMA Mixes) | 0 | Unconditioned | 3 | 3 |
| | | 48 | | 3 | 3 |
| | | 0 | 1 Cycle | 3 | 3 |
| | | 48 | | 3 | 3 |
| | | 0 | Multiple Cycles | 3 | 3 |
| | | 48 | | 3 | 3 |
| Lone Mountain AC-30 | No-Lime (One HMA Mix) | N/A | Unconditioned | 3 | 3 |
| | | | 1 Cycle | 3 | 3 |
| | | | Multiple Cycles | 3 | 3 |
| | Dry Lime to Moist Aggregates (Two HMA Mixes) | 0 | Unconditioned | 3 | 3 |
| | | 48 | | 3 | 3 |
| | | 0 | 1 Cycle | 3 | 3 |
| | | 48 | | 3 | 3 |
| | | 0 | Multiple Cycles | 3 | 3 |
| | | 48 | | 3 | 3 |
| | Lime Slurry to Dry Aggregates (Two HMA Mixes) | 0 | Unconditioned | 3 | 3 |
| | | 48 | | 3 | 3 |
| | | 0 | 1 Cycle | 3 | 3 |
| | | 48 | | 3 | 3 |
| | | 0 | Multiple Cycles | 3 | 3 |
| | | 48 | | 3 | 3 |

Table 2. Resilient modulus mean values at 77$^{o}$F for three replications with the least significant difference for a treatment group.

| Mix | Lime Application | Pooled Variance LSD | Unconditioned | | | 1 Cycle F-T Conditioning | | | 18 Cycles F-T Conditioning | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Mr - Mean ksi | Lower LSD | Upper LSD | Mr - Mean ksi | Lower LSD | Upper LSD | Mr - Mean ksi | Lower LSD | Upper LSD |
| Lockwood AC-20P | No Lime | 30 | 259 | 229 | 289 | 73 | 43 | 103 | * | * | * |
| | Dry Lime, 0-hour | 30 | 214 | 184 | 244 | 118 | 88 | 148 | 112 | 82 | 142 |
| | Dry Lime, 48-hour | 30 | 281 | 251 | 311 | 234 | 204 | 264 | 182 | 152 | 212 |
| | Lime Slurry, 0-hour | 30 | 236 | 206 | 266 | 112 | 82 | 141 | 94 | 64 | 124 |
| | Lime Slurry, 48-hour | 30 | 261 | 231 | 291 | 163 | 133 | 193 | 160 | 130 | 190 |
| Lockwood PG 64-34 | No Lime | 13 | 115 | 102 | 128 | 43 | 30 | 56 | 9 | 0 | 22 |
| | Dry Lime, 0-hour | 13 | 109 | 96 | 122 | 69 | 56 | 82 | 48 | 35 | 61 |
| | Dry Lime, 48-hour | 13 | 98 | 85 | 111 | 93 | 80 | 106 | 56 | 43 | 69 |
| | Lime Slurry, 0-hour | 13 | 102 | 89 | 115 | 80 | 67 | 93 | 58 | 45 | 71 |
| | Lime Slurry, 48-hour | 13 | 91 | 78 | 104 | 80 | 67 | 93 | 38 | 25 | 51 |
| Lone Mountain AC-30 | No Lime | 53 | 509 | 456 | 562 | 121 | 67 | 174 | * | * | * |
| | Dry Lime, 0-hour | 53 | 532 | 479 | 586 | 415 | 362 | 468 | 225 | 171 | 278 |
| | Dry Lime, 48-hour | 53 | 457 | 404 | 510 | 327 | 274 | 381 | 189 | 136 | 242 |
| | Lime Slurry, 0-hour | 53 | 704 | 651 | 758 | 426 | 373 | 479 | 261 | 208 | 314 |
| | Lime Slurry, 48-hour | 53 | 459 | 406 | 513 | 325 | 272 | 378 | 161 | 107 | 214 |
| Average Resilient Modulus Mean, ksi | | | 295 | | | 179 | | | 122 | | |

* Specimens failed during conditioning.

Table 3. Tensile strength mean values for three replications with the least significant difference for a treatment group.

| Mix | Lime Application | Pooled Variance LSD | Unconditioned | | | 1 Cycle F-T Conditioning | | | 18 Cycles F-T Conditioning | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | TS - Mean psi | Lower LSD | Upper LSD | TS - Mean psi | Lower LSD | Upper LSD | TS - Mean psi | Lower LSD | Upper LSD |
| Lockwood AC-20P | No Lime | 14 | 123 | 109 | 137 | 49 | 35 | 63 | * | * | * |
| | Dry Lime, 0-hour | 14 | 104 | 90 | 118 | 113 | 99 | 126 | 81 | 67 | 95 |
| | Dry Lime, 48-hour | 14 | 143 | 129 | 157 | 139 | 125 | 153 | 112 | 98 | 126 |
| | Lime Slurry, 0-hour | 14 | 111 | 97 | 125 | 111 | 97 | 125 | 79 | 65 | 93 |
| | Lime Slurry, 48-hour | 14 | 125 | 111 | 139 | 135 | 121 | 149 | 113 | 99 | 127 |
| Lockwood PG 64-34 | No Lime | 6 | 95 | 89 | 101 | 65 | 59 | 72 | 18 | 12 | 24 |
| | Dry Lime, 0-hour | 6 | 103 | 97 | 109 | 92 | 86 | 99 | 78 | 72 | 84 |
| | Dry Lime, 48-hour | 6 | 86 | 80 | 92 | 83 | 76 | 89 | 70 | 64 | 76 |
| | Lime Slurry, 0-hour | 6 | 102 | 96 | 108 | 86 | 80 | 93 | 75 | 69 | 81 |
| | Lime Slurry, 48-hour | 6 | 84 | 78 | 90 | 78 | 72 | 85 | 65 | 59 | 72 |
| Lone Mountain AC-30 | No Lime | 8 | 150 | 142 | 158 | 53 | 45 | 62 | * | * | * |
| | Dry Lime, 0-hour | 8 | 123 | 115 | 131 | 129 | 120 | 137 | 62 | 53 | 70 |
| | Dry Lime, 48-hour | 8 | 113 | 104 | 121 | 124 | 115 | 132 | 55 | 47 | 63 |
| | Lime Slurry, 0-hour | 8 | 127 | 119 | 135 | 131 | 123 | 140 | 65 | 56 | 74 |
| | Lime Slurry, 48-hour | 8 | 115 | 106 | 123 | 121 | 112 | 129 | 48 | 39 | 56 |
| Average Tensile Strength Mean, psi | | | 114 | | | 101 | | | 71 | | |

* Specimens failed during conditioning.

Table 4. Permanent shear strain mean values at 50°C for three replications with the least significant difference for a treatment group.

| Mix | Lime Application | Pooled Variance LSD | Unconditioned | | | 1 Cycle F-T Conditioning | | | 18 Cycles F-T Conditioning | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Shear Strain Percent | Lower LSD | Upper LSD | Shear Strain Percent | Lower LSD | Upper LSD | Shear Strain Percent | Lower LSD | Upper LSD |
| Lockwood AC-20P | No Lime | 0.142 | 0.968 | 0.826 | 1.110 | 1.479 | 1.337 | 1.621 | * | * | * |
| | Dry Lime, 0-hour | 0.142 | 0.492 | 0.350 | 0.634 | 0.744 | 0.602 | 0.886 | 0.570 | 0.428 | 0.713 |
| | Dry Lime, 48-hour | 0.142 | 0.722 | 0.580 | 0.864 | 0.618 | 0.475 | 0.760 | 0.673 | 0.531 | 0.816 |
| | Lime Slurry, 0-hour | 0.142 | 0.578 | 0.435 | 0.720 | 0.675 | 0.533 | 0.818 | 0.720 | 0.577 | 0.862 |
| | Lime Slurry, 48-hour | 0.142 | 0.725 | 0.583 | 0.868 | 0.817 | 0.675 | 0.959 | 0.612 | 0.469 | 0.754 |
| Lockwood PG 64-34 | No Lime | 0.129 | 0.458 | 0.328 | 0.587 | 0.940 | 0.811 | 1.070 | 1.219 | 1.090 | 1.348 |
| | Dry Lime, 0-hour | 0.129 | 0.459 | 0.330 | 0.588 | 0.415 | 0.285 | 0.544 | 0.550 | 0.421 | 0.679 |
| | Dry Lime, 48-hour | 0.129 | 0.568 | 0.438 | 0.697 | 0.601 | 0.472 | 0.730 | 0.492 | 0.363 | 0.621 |
| | Lime Slurry, 0-hour | 0.129 | 0.540 | 0.410 | 0.669 | 0.552 | 0.422 | 0.681 | 0.574 | 0.445 | 0.703 |
| | Lime Slurry, 48-hour | 0.129 | 0.459 | 0.330 | 0.589 | 0.616 | 0.487 | 0.746 | 0.452 | 0.322 | 0.581 |
| Lone Mountain AC-30 | No Lime | 0.135 | 0.849 | 0.714 | 0.984 | 1.004 | 0.869 | 1.140 | 1.633 | 1.498 | 1.769 |
| | Dry Lime, 0-hour | 0.135 | 0.692 | 0.556 | 0.827 | 0.545 | 0.410 | 0.681 | 0.286 | 0.151 | 0.421 |
| | Dry Lime, 48-hour | 0.135 | 0.522 | 0.387 | 0.658 | 0.555 | 0.420 | 0.691 | 0.354 | 0.219 | 0.490 |
| | Lime Slurry, 0-hour | 0.135 | 0.319 | 0.184 | 0.454 | 0.534 | 0.398 | 0.669 | 0.423 | 0.288 | 0.558 |
| | Lime Slurry, 48-hour | 0.135 | 0.561 | 0.425 | 0.696 | 0.388 | 0.253 | 0.524 | 0.465 | 0.330 | 0.600 |
| Average Shear Strain Mean, % | | | 0.594 | | | 0.699 | | | 0.645 | | |

Table 5. Summary of statistical findings by test procedure for comparison of treatment method.

| Test Procedure | No-Lime Mixtures - VS - Lime Treated Mixtures | | | Method of Lime Treatment |
|---|---|---|---|---|
| | Unconditioned | 1 Cycle Freeze-Thaw Conditioning | Multiple Cycles Freeze-Thaw Conditioning | 1 and Multiple Cycles of Freeze-Thaw Conditioning |
| Resilient Modulus | 11 out of 12 NOT DIFFERENT | 9 out of 12 DIFFERENT | 12 out of 12 DIFFERENT | 30 out of 36 NOT DIFFERENT MIX SPECIFIC |
| Tensile Strength | 8 out of 12 NOT DIFFERENT | 11 out of 12 DIFFERENT | 12 out of 12 DIFFERENT | 31 out of 36 NOT DIFFERENT MIX SPECIFIC |
| Permanent Shear Strain | 7 out of 12 NOT DIFFERENT MIX SPECIFIC | 12 out of 12 DIFFERENT | 12 out of 12 DIFFERENT | 36 out of 36 NOT DIFFERENT |

MIX SPECIFIC - Defines a group of test results specific to a mix which did not follow the trend.

Table 6. Percent coefficient of variation (CV) and required specimens among the mechanical test procedures for each mix and freeze-thaw cycles of moisture conditioning.

| Mix | Method of Lime Application | Resilient Modulus | | | Tensile Strength | | | Permanent Shear Strain | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Uncond. | One F-T Cycle | Multiple F-T Cycles | Uncond. | One F-T Cycle | Multiple F-T Cycles | Uncond. | One F-T Cycle | Multiple F-T Cycles |
| Lockwood AC-20P | No Lime | 22.0 | 19.0 | * | 7.4 | 42.0 | * | 24.1 | 9.0 | * |
| | Dry Lime, 0-hour | 13.4 | 8.9 | 20.8 | 1.0 | 16.5 | 18.5 | 23.4 | 16.9 | 22.0 |
| | Dry Lime, 48-hour | 10.4 | 18.2 | 26.7 | 2.3 | 14.6 | 10.3 | 13.9 | 25.4 | 29.0 |
| | Lime Slurry, 0-hour | 12.5 | 30.1 | 36.6 | 17.2 | 20.6 | 10.1 | 9.2 | 19.8 | 17.9 |
| | Lime Slurry, 48-hour | 6.0 | 23.9 | 32.7 | 15.1 | 15.0 | 18.1 | 11.9 | 37.1 | 38.0 |
| Lockwood PG 64-34 | No Lime | 16.3 | 12.1 | 17.0 | 3.8 | 8.0 | 0.8 | 46.2 | 35.9 | 4.6 |
| | Dry Lime, 0-hour | 18.9 | 15.4 | 5.3 | 9.7 | 13.0 | 9.2 | 20.5 | 6.7 | 56.2 |
| | Dry Lime, 48-hour | 17.7 | 42.3 | 27.2 | 13.0 | 3.8 | 17.0 | 16.4 | 31.2 | 10.3 |
| | Lime Slurry, 0-hour | 13.4 | 7.2 | 9.6 | 4.3 | 8.7 | 2.6 | 23.8 | 17.1 | 23.1 |
| | Lime Slurry, 48-hour | 18.7 | 12.1 | 13.2 | 10.2 | 12.7 | 10.0 | 22.3 | 14.8 | 12.4 |
| Lone Mountain AC-30 | No Lime | 6.7 | 19.9 | * | 14.3 | 8.8 | * | 29.1 | 19.4 | * |
| | Dry Lime, 0-hour | 31.2 | 6.7 | 20.7 | 1.0 | 7.7 | 7.7 | 49.8 | 19.3 | 24.2 |
| | Dry Lime, 48-hour | 12.0 | 13.7 | 27.0 | 4.3 | 4.2 | 23.3 | 15.5 | 23.9 | 11.5 |
| | Lime Slurry, 0-hour | 9.7 | 20.5 | 23.0 | 13.2 | 11.9 | 5.3 | 46.7 | 11.8 | 18.9 |
| | Lime Slurry, 48-hour | 6.0 | 2.4 | 8.5 | 5.5 | 2.3 | 8.8 | 4.0 | 3.2 | 22.8 |
| Average by Conditioning | | 14.3 | 16.8 | 20.6 | 8.2 | 12.7 | 10.9 | 23.8 | 19.4 | 22.4 |
| Average by Test Procedure | | 17.3 | | | 10.6 | | | 21.9 | | |
| Required Specimens by Conditioning Method | | Control | 3 | 5 | Control | 16 | 1 | Control | 38 | 82 |